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Residence time distributions of coarse biomass particles in a screw conveyor reactor

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ABSTRACT

Rotating screw conveyors can be utilized in the application of heat to granular materials: the mechanical motion of the rotating screw provides a controlled means of transferring the product through different thermal sections. This is particularly interesting for thermochemical biomass reactor applications such as slow pyrolysis and torrefaction. To understand the transfer of heat to the biomass, it is necessary to predict the residence time distribution of the material within the rotating screw reactor. Experiments were performed using a bench-scale (2.5 kg/h) rotating screw conveyor. In this work, it has been shown that an empirical mathematical model is sufficient for predicting the mean residence time of various materials (pine chips of different sizes, rice and sand) if the rotational frequency of the screw conveyor and the volumetric throughput rate are both known. The model parameters obtained in this work were found to be independent of material selection but are specific to the geometry of the screw reactor. The form of the mathematical model proposed in this work may be applied to similar applications. Unlike the mean residence times, the axial dispersion calculated from the experimental data showed greater variability and this precluded any predictive modeling.

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1. Introduction

Rotating screw conveyors can be used to transport or elevate granular materials. Despite their widespread application, the understanding of screw conveyors is largely empirical and designs are based on established heuristics incorporating conveyor geometry and material factors. In most situations, such as the pure conveying of material, the residence time of material within the screw conveyor is of minor importance. Subsequently, the emphasis of much research has been limited to the factors influencing the overall volumetric throughput and power requirements of horizontal and inclined screw conveyors. Particle residence times become more important when transient transformations (such as heating, cooling, drying, mixing or chemical reaction) of the solid material need to be controlled [1]. The potential application of rotating screw conveyor reactors to the thermochemical conversion of biomass has been established [2]. In such instances, a relatively low degree of axial dispersion is desired as this ensures uniformity in the length of time that the individual particles are exposed to the desired thermal conditions with a commensurate increase in the uniformity of product quality.

The mechanical action of the rotating screw conveyor pushes particles forward within the spaces between successive flights of the screw housed in the stationary shell or casing. As the flight of the screw moves forward (relative to the shell) the solid material can either be pushed forward or remain stationary by passing through the small clearance spaces between the screw and the shell. Axial dispersion of the particles arise if the particles do not move uniformly through the screw conveyor. The extent of the axial dispersion can be determined by introducing a detectable material (tracer) to a continuous system, either as a small pulse or as a continuous step change. This necessitates that the flow behavior of the tracer must be determined in some way by distinguishing it from the bulk material flow at the outlet of the conveyor. If the use of a tracer is problematic, a step change in the overall bulk flow rate can be introduced when at steady-state conditions and the residence time distribution can be determined by recording outlet flow rates over the period required to reach a new steady state. Alternatively, it is also possible to track the movement of individual particles as they move through the system. This should be repeated for a large number of particles to adequately describe the overall flow behavior. Particle tracking can be done experimentally (visually or by means such as positron emission particle tracking [3,4]) or through computational models (discrete element modeling, computational fluid dynamics) though it is a prerequisite that computational models should be validated against experimental data to ensure computational confidence [1].

Investigations into axial dispersion within mechanical conveyors, (including rotating screw conveyors) have been performed. However, much of the previous work involves screw extruders, twin screw

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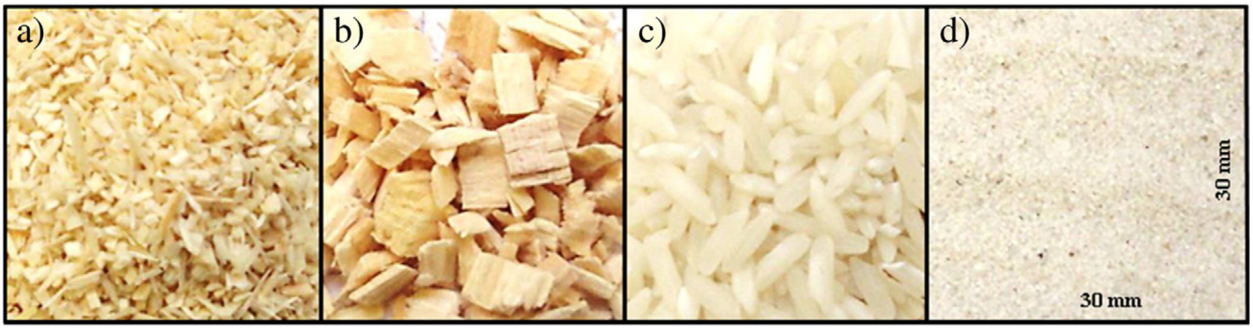

Fig. 1. Feed materials: a) pine a; b) pine b; c) rice; d) sand.

conveyors and rotating drums [5] and limited inferences can be made regarding the operation of single, rotating screw conveyors. The existing research on screw conveyors has utilized fine, dense, homogeneous materials for determining residence time distributions. Tsai and Lin [6] performed experiments by varying conveyor geometry, screw speed, conveyor throughput and combinations of different sizes (1.19 mm–0.5 mm) of steel and alumina balls. Their experiments involved changing the type of steel ball being used when the flow of particles had achieved steady-state conditions. The change in the outlet "composition" was used to generate the residence time distribution. Waje et al. [7] looked at the residence time distribution within a rotating screw conveyor transporting fine sand (0.3 mm–0.425 mm). A pulse input of dyed sand was used as a tracer and the material, periodically sampled at the outlet of the conveyor, was washed to recover and quantify the amount of dye as a function of time. Waje et al. [8] performed residence time distribution experiments based on step changes in the total feed of sand (mean diameter of 0.363 mm) to the screw conveyor to determine the residence time distributions and determined that axial dispersion was mostly dependent on the rotational frequency of the screw and the loading of material to the screw. In contrast to previous research, this work focuses on solid particles which display different bulk properties: pine chips, and rice are used in this work as these are more typical feed materials for thermochemical biomass conversion. As these materials are less dense, less spherical and have a greater particle size range than the steel and sand particles used in other research, possible changes in the flow behavior need to be accounted for. Additionally, sand particles were also used to allow a comparison of the experimental results obtained within this work with previously published results.

The overall aim of this work is to gain sufficient understanding of residence times and axial dispersion to allow for the modeling of the thermochemical transformations that take place within coarse biomass particles (defined in this work to be material with a sieving diameter of more than 1 mm) when undergoing torrefaction and slow pyrolysis in screw conveyor reactors. An attempt to model mean residence times in screw conveyors has not been undertaken in the academic literature to the best of the authors' knowledge. This work does not address the radial dispersion within the screw conveyor which could be an important factor in understanding the transfer of heat to the biomass in the case of indirect heat transfer through the screw conveyor shell.

2. Materials and methods

2.1. Feed materials

Air-dried pine chips (BEMAP, The Netherlands) of two different particle size distributions; dehulled rice (Econom long grain rice, Colruyt Group, Belgium); and quartz sand (P.T.B.-Compaktuna, Belgium) were all used in their form as received. The particle size distribution (PSD) analyses of the feed materials were determined by sieving (AS 200 sieve shaker, Retsch, Germany) and the maximum particle length was determined by inspection of a random sample (100 ml) of particles. The untapped bulk densities were calculated by weighing the mass of material poured into a 1 l beaker. The angle of repose was measured by increasing the angle of a flat bed of material on a stainless steel tray and reporting the angle of inclination at the moment of initial movement, yielding results typical of free flowing particulate materials [9]. The feed materials are shown in Fig. 1, while the measured properties of the feed materials are summarized in Table 1.

2.2. Feed screw and screw conveyor

The experiments were carried out in a system of two, horizontal, stainless-steel screw conveyors operating in series. The first, smaller screw conveyor (referred to as the feed screw) which operated as a variable-rate feeder, was used to introduce material to the larger screw (referred to as the screw conveyor). The feed screw passes through a cylindrical feed hopper which is mechanically agitated to promote the uniform introduction of material to the feed screw. The rotational frequencies of the feed screw and screw conveyor are independently controlled. The mass-based throughput of the system is dependent on the biomass properties: for pine B, it is known to be in the order of 2.5 kg/h. The dimensions and rotational frequencies of

Table 1
Properties of feed materials.

	Pine A	Pine B	Rice	Sand
PSD (wt.%)				
> 4 mm	0.0%	18.6%	0.0%	0.0%
4 mm–2 mm	0.2%	66.0%	9.7%	0.0%
2 mm–1 mm	57.8%	12.5%	90.3%	0.1%
1 mm–0.5 mm	38.1%	1.9%	0.0%	7.9%
0.5 mm–0.25 mm	3.2%	0.5%	0.0%	65.7%
0.25 mm–0..075 mm	0.4%	0.3%	0.0%	26.0%
<0.075 mm	0.3%	0.2%	0.0%	0.3%
Maximum particle length (mm)	2.5	16.5	6.5	1.5
Bulk density (kg/m^3)	155.4	165.4	862.1	1559.0
Angle of repose	30°	31.3°	26.7°	27.7°

Table 2
Dimension of the feed screw and screw conveyor.

	Feed screw	Screw conveyor
Length (from inlet to outlet) (m)	0.300	1.640
Shell diameter (m)	0.044	0.052
Screw diameter (m)	0.042	0.050
Radial clearance (m)	0.001	0.001
Shaft diameter (m)	0.018	0.018
Pitch (m)	0.042	0.046
Flight thickness (m)	0.003	0.003
Maximum frequency (Hz)	1.205	0.486

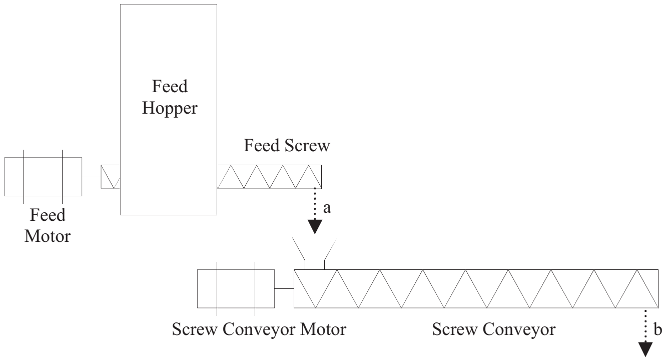

Fig. 2. Schematic drawing of screw conveyor system with measurement positions for a) feed screw experiments; b) screw conveyor experiments.

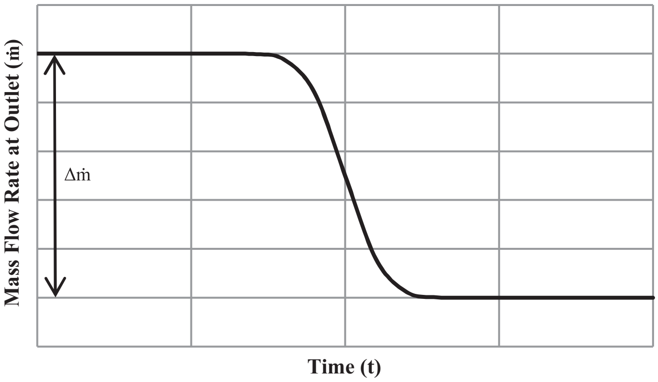

Fig. 3. Hypothetical response curve for a negative step change in the inlet flow rate.

the feed screw and screw conveyor are summarized in Table 2 and a schematic drawing of the system is given in Fig. 2. Feed conveyor experiments were carried out at the maximum feed screw frequency for different feed materials. The screw conveyor step-change experiments were carried out at different combinations of feed screw and screw conveyor frequencies: 100%, 75%, 50% and 25% of their maximum values.

2.3. Data capturing

Mass flow rates ($\dot{m}$) were determined by weighing the mass of material exiting either the feed screw or the screw conveyor at regular time intervals (10 s) and capturing these weights over time. These intervals need to be large enough to capture sufficient material for the sensitivity of the used scales (Combics CAW1P, Sartorius Weighing Technology GmbH; 2 g resolution and FCB3KO.1, Kern & Sohn GmbH; 0.1 g resolution) but small enough so that transient changes in flow rates could be observed. Initially, experiments involved only the feed screw and these entailed measuring the magnitude and uniformity of the flow rate produced for different materials. Thereafter, the residence time distributions within the screw conveyor were determined. This was done by running the system at steady-state conditions and introducing a negative step change (switching off the feed screw and stopping the biomass from being introduced into the screw conveyor). The reference time at which the feed screw is stopped is taken as t_0. During these experiments, it was observed that the outlet flow rate did not always decrease monotonically. Although each experiment was treated in the same way, these fluctuations introduce some errors into the calculated results. All experiments were performed in duplicate in order to determine the repeatability of the results.

2.4. Theoretical background

The experimentally observed residence time distributions were used for the calculation of the conveyor inventory, degree of filling, mean residence time and the residence time variance which were used further to quantify axial dispersion through the calculation of the number of ideal continuous-stirred tank reactors in series and the Péclet number. These calculations are briefly discussed below. More detailed description can be found in literature [8,10–12].

For a negative step change in the mass flow rate ($\Delta\dot{m}$), the response curve can have a shape similar to that given in Fig. 3.

From a mass balance, the decrease in the screw conveyor inventory can be calculated by integrating the difference between inlet and outlet flows with respect to time. For the special case that the conveyor inlet flow rate is completely stopped at time t_0, the total mass of material held within the screw conveyor (m) prior to the step change may be determined for that given flow rate,

$$m = \int_{t_0}^{\infty} \dot{m}\,(t)dt \tag{1}$$

where $\dot{m}(t)$ is the mass flow measured at the screw conveyor outlet rate at time, t.

Since the volume of the screw conveyor (V) can be calculated from its geometry and the volume of the material can be calculated from the inventory (m) and bulk density (ρ_m), it is possible to determine the of the volume in the screw conveyor that is occupied by the solid material as,

$$\alpha = \frac{m}{\rho_m \times V} \tag{2}$$

where α is the fractional degree of filling. Changes in the degree of filling have been shown to result in changes in the flow pattern of particles within the screw conveyor [8].

The ideal linear forward movement of a particle in the screw per complete rotation of the screw is equal to the pitch of the screw (p). Under such conditions, no particles pass between the screw and the shell and all particles spend the same amount of time within the conveyor: no axial dispersion. The theoretical ideal residence time (τ_{ideal}) can be calculated directly if the screw geometry and the rotational frequency of the screw conveyor (ν) are known. The theoretically ideal time taken for a particle to travel the distance between the conveyor inlet and outlet (l) is calculated as:

$$\tau_{ideal} = \frac{l}{p \times v} \tag{3}$$

The cumulative residence time distribution function ($F(t)$) for a step change is determined by dividing the change in mass flow rate at a given time by the size of the step change to yield a distribution that increases from 0 to 1:

$$F(t) = \frac{\dot{m}_0 - \dot{m}\,(t)}{\dot{m}_0} \tag{4}$$

The mean residence time (τ) can then also be calculated by integrating time (t) over the span of the cumulative distribution function:

$$\tau = \int_0^1 t dF \tag{5}$$

The distribution of the observed residence times relative to the mean residence time is analogous to the variance of a continuous probability distribution (σ^2):

$$\sigma^2 = \int_0^1 (t-\tau)^2 dF \tag{6}$$

Comparisons between the residence time distribution variances and the mean residence time can be expressed in a number of ways, thereby indicating how the observed distribution can be modeled by different theoretical combinations of plug-flow reactors (PFRs) and continuous-stirred tank reactors (CSTRs). The ideal PFR assumes that no axial dispersion is possible and that all particles spend an identical time (equal to the mean residence time) in the conveyor. At the other extreme, a CSTR assumes that perfect mixing is achieved [1]. In this work, two measures of comparing the axial dispersion are calculated and reported, namely the number of CSTRs in series (N) and the Péclet number (Pe). The calculation of the number of theoretical CSTRs operating in series is defined by the ratio:

$$N = \frac{\tau^2}{\sigma^2} \tag{7}$$

Thus for an ideal PFR, where there is no axial dispersion, σ^2 will be zero and N will be infinite. For an ideal CSTR, N will logically be 1.

The inverse of N scales the observed variance of the residence time distribution to the square of its mean residence time, yielding:

$$\sigma_D^2 = \frac{\sigma^2}{\tau^2} \tag{8}$$

where $\sigma_D{}^2$ is the dimensionless variance of the residence time distribution. The Péclet number (Pe) is a ratio of the rate of convective, bulk transport to the rate of axial dispersion taking place [10]. The Péclet numbers reported in this work were calculated by [11]:

$$Pe = \frac{8}{\sqrt{8\sigma_D^2 + 1} - 1} \tag{9}$$

Increasing Péclet numbers indicate that a flow is more comparable to ideal plug-flow. An ideal PFR, where no axial dispersion takes place, would have an infinite Péclet number.

The mathematical model proposed in this work is of the form given below:

$$\tau_{mod\ el} = \frac{1}{p \times v_{screw}} \times \left(k_0 + k_1 \frac{Q}{v_{screw}}\right) \tag{10}$$

where τ_{model} is the estimated mean residence time. The first term of this equation gives the ideal reactor residence time as calculated by conveyor geometry in Eq. (3). The basis for this form of the model is the assumption that the degree of non-ideality is a linear function of the degree of filling of the conveyor (here expressed as the volumetric flow rate within the screw (Q) and screw conveyor frequency (ν_{screw}). The model coefficients (k_0 and k_1) are estimated through the minimization of square errors between the modeled and experimental mean residence times.

Table 3
Analysis of the variability in the feed screw flow rates (determined by measuring at 10 s intervals) at maximum rotational frequency (1.205 Hz).

Material	Average mass flow rate	Standard deviation	Coefficient of variation	Average volumetric flow rate
	(g/s)	(g/s)	(−)	(l/s)
Pine A	3.9	0.3	0.08	0.025
Pine B	2.1	0.2	0.11	0.013
Rice	28.6	1.0	0.04	0.035
Sand	38.9	1.1	0.03	0.025

3. Results and discussion

3.1. Feed conveyor experiments

Initial experiments based on the performance of the feed screw have shown that there is a degree of variability in the rate at which feed material is delivered to the screw conveyor. The variable feed rates are indicative of how unevenly material is transferred from the feed hopper to the feed screw. The PSD data given in Table 1 can be misleading: sieving determines the two minimum orthogonal dimensions of the particles and, in the case of feeding material into a conveyor, it is the largest dimensions that will give a better idea of whether the material can pass through the conveyor adequately. The comparable mass and volumetric flow rates for the different feed materials at maximum feed screw frequency (1.205 Hz) are shown in Table 3. The volumetric throughput of the feed screw was seen to depend on the feed material selection, indicating differing efficiencies in which the feeding screw draws material from the hopper. The material with the larger particle size (pine B) is affected more dramatically by the geometric limitations and this also results in an increase in the coefficient of variation (which is defined as the standard deviation divided by the average value of a distribution). Based on these preliminary results it appears that in order to maximize the volumetric feed rate one would require the material to have a narrow particle size distribution significantly smaller than the clearance within the screw and the shaft and larger than the radial clearance (distance between the outer edge of the screw and the shell). The material should also exhibit a high flowability: a characteristic of which all the materials under investigation possess (as indicated by a low angle of repose in Table 1).

3.2. Screw conveyor step-change experiments

It should also be noted that some combinations of feed screw and screw conveyor frequencies were not possible to analyze, particularly when using a high feed screw frequency in combination with a low screw conveyor frequency. Such overloading of the screw conveyor resulted in a blockage at the screw conveyor inlet. To give a graphical representation of the effect of increasing the feed rate to the screw conveyor, Fig. 4 shows the response in the outlet flow rates for the negative step changes when the screw conveyor operates at its maximum frequency (0.486 Hz). One can see that when the feed rate to the screw conveyor is increased, the time at which the outlet flow starts

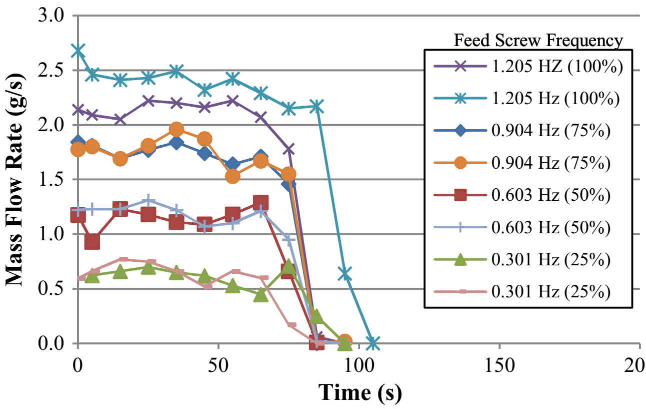

Fig. 4. Impact of a negative step change (feed stopped at $t = 0$ s) on the outlet flow rate of the screw conveyor (Pine B) at various feed screw frequencies—screw conveyor operating at 0.486 Hz (100% of maximum frequency).

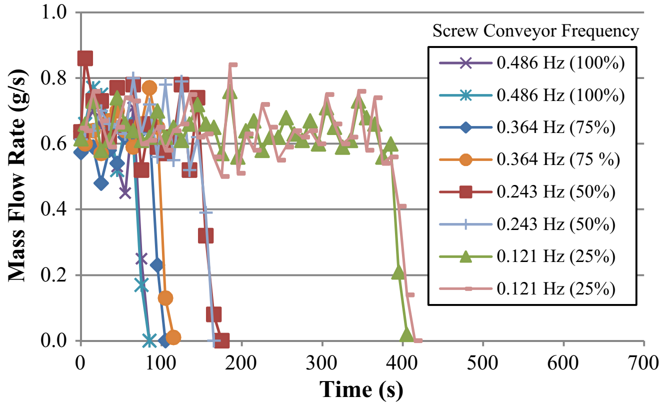

Fig. 5. Impact of a negative step change (feed stopped at $t = 0$ s) on the outlet flow rate of the screw conveyor (Pine B) at various screw conveyor frequencies—feed screw operating at 0.301 Hz (25% of maximum frequency).

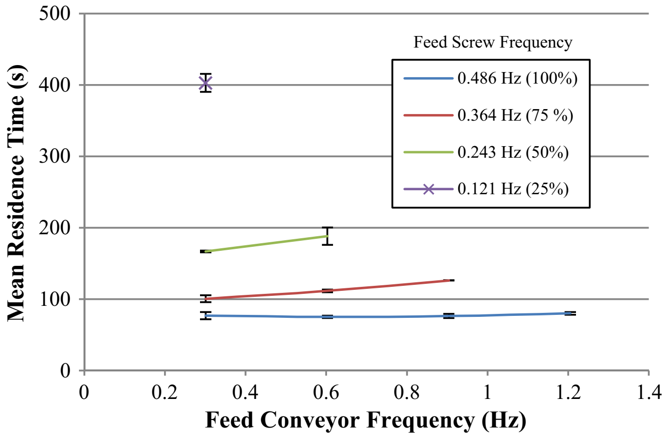

Fig. 6. Effect of feed screw and screw conveyor frequencies on mean residence time (Pine B).

to decrease is increased. The variability in the steady-state flow rate prior to the decrease in the outlet flow rate is also observable. It should also be borne in mind that the material leaves the screw in periodic pulses. Since the mass sampling frequency is not a multiple of the discharge frequency some variability is unavoidably introduced in addition to the variability in the feed delivered to the screw. It would be possible to smooth the curves mathematically, but for the purposes of this work such manipulation of the raw data was avoided.

Fig. 5 shows that, by increasing the frequency of the screw conveyor one can directly decrease the time taken to achieve the steady state (and therefore also the mean residence time). This is an obvious consequence of the screw pushing material through more rapidly at higher frequencies. One can see that the outlet flow rate decreases quite abruptly in all instances.

The experimental results of the screw conveyor experiments are summarized in Table 4 for the different combinations of feed screw frequencies (ν_{feed}) and screw conveyor frequencies (ν_{screw}). The standard deviations are included to indicate how variable the results were for repeated experiments at the same conditions. In all cases, the calculated

Table 4
Hydrodynamic results for screw conveyor residence time experiments for different feed materials and for different feed screw and screw conveyor frequencies.

Feed screw frequency	Screw conveyor frequency	Flow rate	Degree of filling	Mean residence time		Axial dispersion	
ν_{feed}	ν_{screw}	$\dot{m}$	α	τ_{ideal}	τ	N	Pe
(Hz)	(Hz)	(g/s)	(−)	(s)	(s)	(−)	(−)
Pine A							
0.904	0.486	3.31 ± 0.23	0.86 ± 0.01	73.4	102.9 ± 3.3	353 ± 125	711 ± 251
0.603	0.486	2.31 ± 0.1	0.47 ± 0.01	73.4	93.9 ± 2.6	863 ± 396	1730 ± 792
0.301	0.486	1.18 ± 0.04	0.2 ± 0	73.4	78.5 ± 0.8	232 ± 25	468 ± 50
0.603	0.364	2.44 ± 0.06	0.71 ± 0.02	97.2	132.1 ± 1	426 ± 153	856 ± 307
0.301	0.364	1.25 ± 0.03	0.27 ± 0	97.2	107.2 ± 2	404 ± 120	813 ± 240
0.301	0.243	1.25 ± 0.02	0.46 ± 0.01	143.8	186.4 ± 3.9	2708 ± 1497	5420 ± 2995
Pine B							
1.205	0.486	2.41 ± 0.38	0.37 ± 0.07	73.4	80 ± 1.8	149 ± 112	303 ± 224
0.904	0.486	1.81 ± 0.05	0.27 ± 0	73.4	76.3 ± 2.9	127 ± 74	258 ± 149
0.603	0.486	1.2 ± 0.03	0.17 ± 0.01	73.4	75.1 ± 1.8	139 ± 4	283 ± 7
0.301	0.486	0.61 ± 0.02	0.09 ± 0	73.4	77 ± 5.1	303 ± 96	610 ± 192
0.904	0.364	1.84 ± 0.09	0.45 ± 0.02	97.2	126.2 ± 0.3	717 ± 166	1437 ± 331
0.603	0.364	1.23 ± 0.05	0.27 ± 0	97.2	111.5 ± 2	1521 ± 878	3045 ± 2506
0.301	0.364	0.61 ± 0.05	0.12 ± 0.01	97.2	100.5 ± 4.8	1255 ± 707	2869 ± 1755
0.603	0.243	1.18 ± 0.15	0.43 ± 0.08	143.8	188.3 ± 12	1037 ± 187	2514 ± 1414
0.301	0.243	0.62 ± 0.02	0.2 ± 0	143.8	166.7 ± 1.3	2515 ± 1532	2078 ± 373
0.301	0.121	0.63 ± 0.02	0.49 ± 0	287.7	402.9 ± 12.6	100 ± 100	5034 ± 3064
Rice							
0.904	0.486	21.01 ± 0.06	0.86 ± 0.01	73.4	106.6 ± 1.3	706 ± 322	1630 ± 344
0.603	0.486	14.37 ± 0.12	0.47 ± 0.01	73.4	85.7 ± 0.8	286 ± 154	1202 ± 102
0.301	0.486	6.98 ± 0.05	0.2 ± 0	73.4	74.1 ± 0.9	331 ± 61	751 ± 90
0.603	0.364	14.25 ± 0.01	0.71 ± 0.02	97.2	130.2 ± 3.2	771 ± 295	2012 ± 12
0.301	0.364	7 ± 0.03	0.27 ± 0	97.2	100.4 ± 2.3	571 ± 360	1225 ± 197
0.301	0.243	7.01 ± 0.03	0.46 ± 0.01	143.8	170.8 ± 3	1092 ± 460	4722 ± 2491
Sand							
0.904	0.486	7.96 ± 0.5	0.78 ± 0.01	73.4	113.3 ± 3.6	813 ± 172	1630 ± 344
0.603	0.486	5.35 ± 0.2	0.46 ± 0.01	73.4	99.4 ± 1.7	599 ± 51	1202 ± 102
0.301	0.486	2.7 ± 0.07	0.21 ± 0	73.4	93.3 ± 2.7	373 ± 45	751 ± 90
0.603	0.364	3.85 ± 0.16	0.65 ± 0	97.2	146.3 ± 4.9	1004 ± 6	2012 ± 12
0.301	0.364	1.96 ± 0.06	0.27 ± 0	97.2	125.5 ± 2	611 ± 99	1225 ± 197
0.301	0.243	0.97 ± 0.35	0.44 ± 0	143.8	204.5 ± 6.4	2359 ± 1246	4722 ± 2491

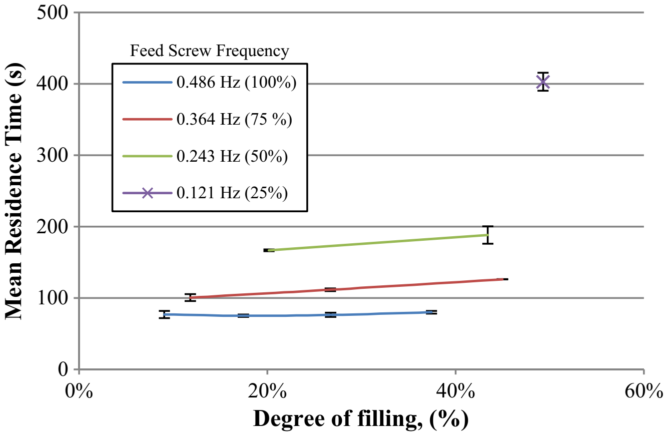

Fig. 7. Effect of screw conveyor frequencies and degree of filling on mean residence time (Pine B).

mean residence times were longer than the ideal residence times, indicating that, on average, particles were traveling forward along the screw conveyor at a slower rate than the geometry of the screw conveyor would ideally allow. Large variations were observed when determining the axial dispersion from the residence time distributions through the calculation of both the number of CSTRs in series and the Péclet numbers. This could be due to the variations in the feeding rate of material into the conveyor. The asynchronicity between the sampling frequency and the frequency at which the material is discharged due to its pulse-like flow behavior could also increase variability in the calculated residence time distribution variances and this would tend to increase the variability of both the calculated number of CSTRs in series and Péclet numbers.

3.2.1. Effect of feed screw frequency

The results indicate that increasing the feed rate to the screw conveyor also increases mean residence times. This trend is consistent for the different material types, as shown in Table 4 and presented for pine B in Fig. 6. Increasing the feeding rate for a constant screw conveyor frequency would necessarily result in an increase in the degree of filling in the screw conveyor. It is proposed that the increase in the degree of filling within the screw conveyor increases the prevalence of any material slipping between the screw and the shell of the conveyor or passing over the shaft of the screw conveyor. This movement of material may be regarded as a backward slippage relative to the forward motion of the propagating screw. Since this slippage can only delay the time at which the material exits the screw conveyor it would tend to increase mean residence times with increased degrees of filling, as supported by Fig. 7. The error bars indicated in Figs. 6 and 7 indicate one standard deviation above and below the average obtained from repeat experiments.

This backward slippage would also result in increased axial dispersion, thereby resulting in smaller *N* and *Pe* values. Given the large variations of the *N* and *Pe* values reported in Table 4 it is difficult to discern such a trend. The high *N* and *Pe* values are an indication that the flow rate of material leaving the screw conveyor changes abruptly after remaining relatively constant for a significant period of time (as indicated in Figs. 4 and 5). In the absence of a strict numerical criteria for which the assumption of plug-flow behavior can be accepted, the classification of the flow as being plug-flow remains subjective. It is dependent on the intended application of this data whether the mean residence time can be used to adequately describe the residence time of all particles.

The work of Waje et al. [7,8] indicated that the increase in the residence time is to be expected; however, they also showed that this

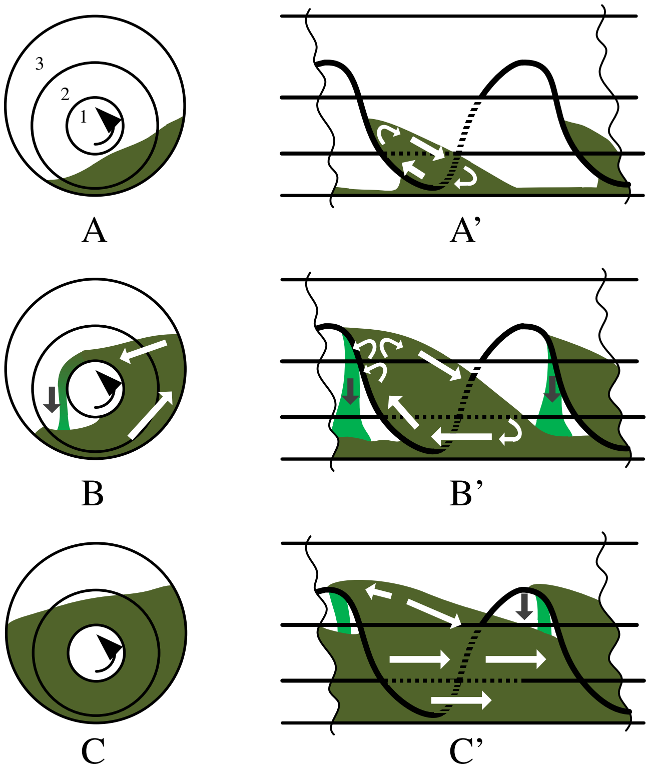

Fig. 8. Flow patterns inside a screw conveyor (1: shaft; 2: screw flight; 3: screw conveyor shell; arrows indicate the flow direction); A, B, C: front view and A′, B′, C′: side view. After [8].

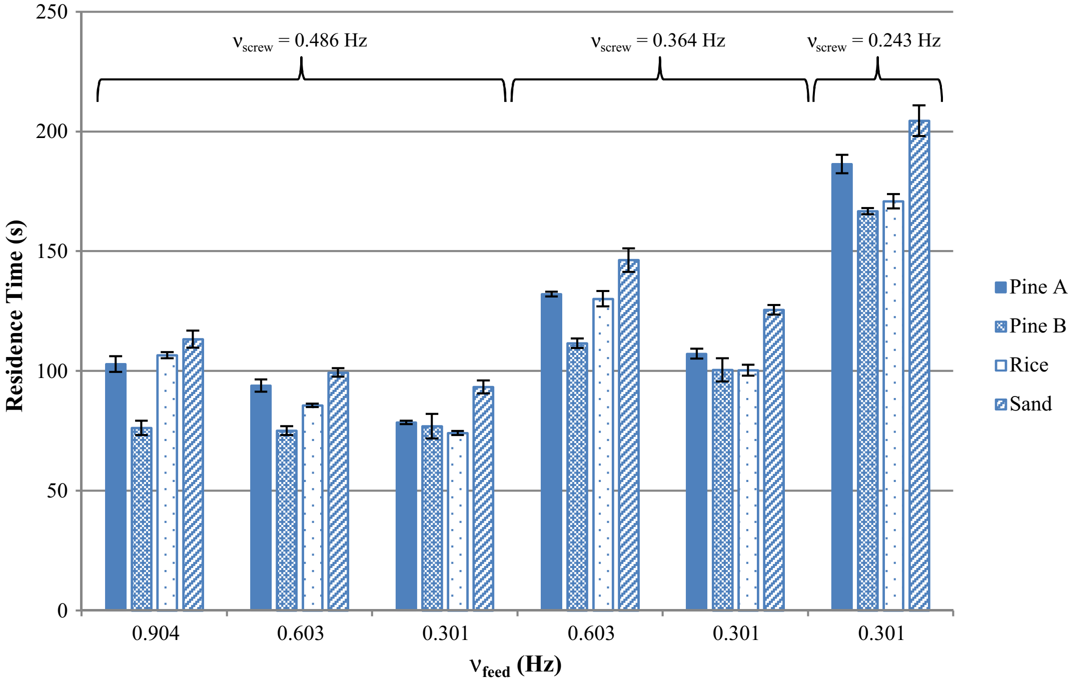

Fig. 9. Comparison of mean residence times for different materials at different combinations of feed screw and screw conveyor rotational frequencies.

trend reverses (at least for the fine materials that they used) once the feed to the screw is large enough that the level of material on a trailing section of the screw is very high, as this can reduce the flow of material slipping between the shell and screw relative to the material being pushed forward, as shown in Fig. 8. The results from the experiments in this work do not indicate such behavior.

3.2.2. Effect of the screw conveyor frequency

It is evident from Fig. 5 that there is an increase in mean residence times when the rotational frequency of the screw conveyor is reduced. This behavior is expected, as reducing the screw conveyor frequency directly reduces the screw propagation speed relative to the shell of the conveyor. This can also be seen in the changes in τ_{ideal} given in Table 4. One may expect that an increase in the screw conveyor frequency would increase the likelihood of particles being flung over the shaft rather than being pushed forwards, thereby increasing residence times and axial dispersion, similar to results seen elsewhere in discrete element modeling research [12]. Again, the analysis of the experimental data yields ambiguous results in terms of any observable trends in axial dispersion. The results from the experiments performed by Tsai and Lin [6] have shown that the axial dispersion can, in fact, decrease with increasing screw frequencies although these experiments were carried out below 0.05 Hz and these very low speeds could differ fundamentally from the results of this work. Their argument was that the increased rotational frequencies would reduce the residence time of material within the conveyor and therefore would reduce the time available for mixing; however the calculation of the axial dispersion, as shown in Eq. (7), is scaled to allow for changes in mean residence times.

3.2.3. Effect of material selection

It has already been shown in Table 3 that material selection has an impact on the mass and volumetric flow rates at which the material is introduced into the screw conveyor by the feed screw. The effect of material selection on the mean residence times within the screw conveyor for different combinations of feed screw and screw conveyor frequencies is summarized in Fig. 9. The error bars indicate one standard deviation above and below the average obtained from repeat experiments. The results vary somewhat but it appears that the materials which consist of smaller particles (such as pine A and sand) display longer residence times, possibly due to the increased likelihood for material to pass between the screw and the shell of the screw conveyor. Pine B and rice could be seen as the most ideal material as they pass through the screw conveyor the fastest. Relatively large values of *N* and *Pe* are reported in Table 4. In other work based on single screws [6–8], greater axial dispersion is observed (lower *N* values, ranging from 12 to 100) than in this work. Since the particle size distribution of the material has an impact on the mean residence times, any changes in the particle size reduction through attrition and abrasion within the screw conveyor could skew results. It is also known that torrefied biomass and pyrolysis char are more readily ground than biomass [13] and this is an inevitable short-coming in applying the conclusions that may be drawn from these results to such applications.

3.3. Modeling of screw reactor residence times

The experimental results have suggested that the mean residence times achieved in the screw conveyor do follow some general trend. For the purpose of this work, it is assumed that the changes in mean residence times can be determined from the operating conditions as shown in Eq. (10). The model coefficients (k_0 and k_1) were determined in a combined regression for all the experimental results obtained in this work (combining the results for the different feed materials). The coefficients that were determined through the model fitting are given in Table 5. Table 5 also shows the generalized R^2 values, indicating the degree to which the model can explain the observed experimental results. The results from the model fitting are shown as a parity plot in

Table 5
Coefficients determined by fitting residence time model to experimental results.

k_0 (−)	0.995
k_1 (Hz/(m^3/h))	2.959
R^2	0.993

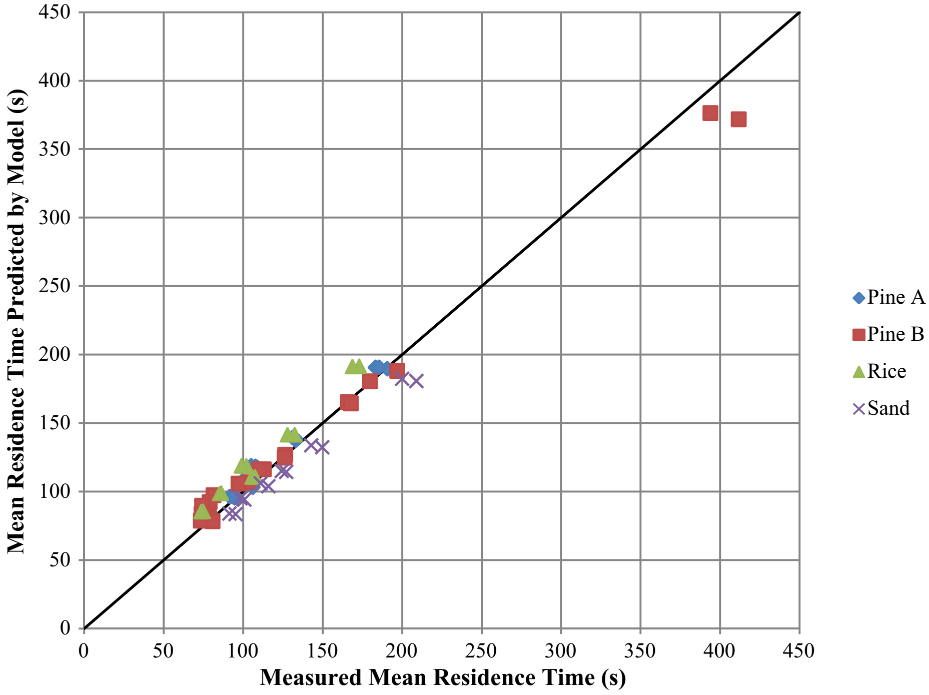

Fig. 10. Parity plot for modeled and experimental mean residence times.

Fig. 10. One of the limitations of this model is that it is specific to the selection of feed materials and the screw conveyor geometry used in this work. The results do, however, indicate that this methodology may be used to estimate mean residence times in other instances where some, limited data is available. Also, it may be possible to estimate mean residence times for one material based on data from another since it has been shown that the values of k_0 and k_1 are not material-specific (at least for the range of materials considered in this work). Ideally, it would be desired to determine the model coefficients (k_0 and k_1) in terms of a greater range of particle and screw conveyor properties; however, a significantly larger dataset (utilizing different screw conveyors and feed materials) would be needed to make such inferences. It is interesting to note that, for the results obtained in this work, it seems that $k_{0,}$ has an estimated value close to 1. This implies that, at low volumetric flow rates (where Q approaches 0), the mean residence time approaches the ideal value which may be calculated from screw geometry. This is best seen in Table 4, where it is observable for all materials that the calculated residence time (τ) approaches the ideal value (τ_{ideal}) when the feed frequency (ν_{feed}) is reduced and the screw conveyor frequency (ν_{screw}) is kept constant. At increased volumetric flow rates, the residence appears to deviate from this ideal value in proportion to the volumetric flow rate and in inverse proportion to the frequency of the screw conveyor.

The low degree of axial dispersion witnessed during these experiments and the high variability seen in the calculated N and Pe values prevent any empirical conclusions from being drawn from the available data. While one could subjectively conclude that the flow of material may be seen as ideal plug-flow, it is specific to the intended application to determine whether the distribution of the particle residence times allows for such a theoretical simplification.

4. Conclusions

The ideal residence time can be calculated from the conveyor geometry and rotational frequency but it significantly underestimates the experimentally observed mean residence time of material within the conveyor. The deviation from the ideal residence time can be estimated from the knowledge of the volumetric feed rate and the screw conveyor frequency if sufficient data has been captured to allow the calculation of two empirical parameters which describe the behavior of the screw. These parameters were found to be independent of material selection and this points to the potential of using the empirical relation for materials beyond those included in this work (although the sensitivity of these parameters to screw conveyor geometry should be investigated further). Subjectively, it may be concluded that the conveying of both coarse and fine granular material by a rotating screw can reasonably be assumed to behave in a plug-flow manner; however, the efficacy of such a simplification is dependent on the requirement of the system that is being described or modeled. The slippage of material between the screw and the shell of the conveyor is promoted by increasing the feed rate to the screw conveyor or by decreasing the screw frequency, thereby increasing mean residence times. No trends could be discerned regarding changes in the calculated axial dispersion parameters (N and Pe).

Nomenclature

Symbols

d_{screw}	Conveyor screw diameter (m)
F	Cumulative residence time distribution function
H	Mass hold-up (kg)
k_0	Experimental coefficient for residence time calculation (—)
k_1	Experimental coefficient for residence time calculation (—)
l	Distance between inlet and outlet points of the screw conveyor (m)
m	Mass of particles in screw inventory (kg)
$\dot{m}(t)$	Outlet mass flow rate at time t (kg/s)
$\dot{m}_0$	Outlet mass flow rate prior to step change (kg/s)
$\dot{m}_\infty$	Outlet mass flow rate after step change at new steady state (kg/s)
N	Number of theoretical CSTRs in series (—)
p	Screw pitch (m)
Pe	Péclet number (—)
Q	Volumetric flow rate (m^3/h)
t	Time (s)
t_0	Time at which inlet feed is started (s)
V	Volume of the screw conveyor (m^3)

Greek letters

α	Fractional degree of filling (−)
ν_{feed}	Feed screw rotational frequency (Hz)
ν_{screw}	Screw conveyor rotational frequency (Hz)
σ^2	Variance of the residence time distribution (s^2)
$\sigma_D{}^2$	Dimensionless variance of the residence time distribution (−)
ρ_m	Material bulk density (kg/m^3)
τ	Mean residence time calculated from residence time distribution (s)
τ_{ideal}	Mean residence time calculated from screw geometry (s)
τ_{model}	Mean residence time calculated from residence time distribution (s)

Abbreviations

CSTR	Continuous-stirred-tank reactor
PFR	Plug-flow reactor
PSD	Particle size distribution

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